JOHNSTOWN TRANSMISSION LINE

OF THE

EAST CREEK, ELECTRIC LIGHT & POWER CO., NEW YORK

BY

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ARMOUR INSTITUTE OF TECHNOLOGY

1915

Design of a Transmission Line.
Johnstown Transmission Line
of the East Creek Electric Light
and Power Company, New York.

A THESIS

PRESENTED BY

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DESIGN OF A TRANSMISSION LINE.

Johnstown Transmission Line of the East Creek Electric Light and Power Company, New York.

BLUE PRINTS.

Plan and profile of 27.65 miles of line.

Regulation chart.

Standard rigid tower.

Standard flexible tower.

Chart for sag at different temperatures showing pull on dynamometer.

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Length of line ------------ 53 miles.

Rating of line ------------ 26,000 k.v.a.

Power factor of line ------ 0.8.

For equal conductance aluminum is lighter and therefore easier to string. The spans are comparatively short (about 580') so that height of towers will not be affected by material used. "For equal conductance aluminum is approximately 10% cheaper than copper." -------

Delmar in "Electric Power Conductors".

Selling price of power ---- per h.p. year = $18.00.

The supply exceeds the demand during the first ten years of operation.

Cost of producing power ---- per h.p. year = $6.00.

Estimated life of conductors ------ 20 years.

Average cost of wasted power during the 20 years life of the conductors is --------.

$$p_1 = \frac{(10 \times 6) + (18 \times 10)}{20}$$

$$= \$12.00.$$

ECONOMIC VOLTAGE DROP:

$$e_r = 5.66 \sqrt{\frac{a \times p}{p_1}}$$

p = price to be paid for 100# of conductor, = \$42.00.

a = percentage to cover annual interest and depreciation

= 3% + 7% = 10%.

$$e_r = 5.66 \sqrt{\frac{10 \times 42}{12}} = 33.5 \text{ volts.}$$

First approximation to the required line voltage:

$$V = 5.5 \sqrt{L}$$

L = distance of transmission (in miles) + $\frac{\text{horse power transmitted.}}{200}$

$$V = 5.5 \sqrt{53 + \frac{27,900}{200}}$$

= 76.5 or say 80,000 volts.

FINAL DETERMINATION OF VOLTAGE;

Yearly charges on conductors =

$$\frac{2 \times \sqrt{3} \times e_r \times P \times p_1 \times l}{E \times \cos\theta}.$$

P = h.p. transmitted.

= 27,900.

Z = length of line in miles

= 53.

cos θ = 0.8.

E will be taken as 80,000 and 88,000.

When E = 80,000 yearly charges = $32,200.00

When E = 88,000 " " = $29,300.00.

Portion of complete undertaking affected by change of voltage.	Estimated life in years.	Depreciation.	Depreciation.+7%.	Total Cost.		Annual Charges.	
				80000	88000	80000	88000.
Line conductors of most economic section. (annual cost varies as $\frac{1}{\text{voltage}}$)	20					30200	29300
Steel tower transmission line, without conductors, but otherwise complete.	18	3.55	10.55	137800	148400	14500	15650
Transformers	18	3.55	10.55	60500	62600	6380	6600
Generator station buildings.		Assume unaltered.					
Sub-station buildings.		Assume unaltered.					
Switch gear, including lightning arresters, cables in buildings and entering bushings.	14	5.10	12.10	63300	69660	7650	8425
Assume unaltered: Yearly cost of power lost in generators and in transformers, yearly cost of operation and maintenance, right of way and clearing		Difference in favor of 88000 = $755.00				60730	59975

Voltage (line) of transmission line

= 88,000.

Line current $= \dfrac{26,000,000}{\sqrt{3} \times 88,000} = 170.5$ amperes

Resistance per mile of conductor $= \dfrac{E}{I} =$

$\dfrac{33.5}{170.5} = 0.197$ ohms.

DATA ON WIRE CHOSEN:

Circular Mils.	diam.	area sq. inches.	pounds per 1000'
395,150	0.72"	0.3103	363.5

ft. per pound	ohms per 1000'	el. limit.	ult.strength
2.7511	0.04289	4340#.	8,070#

Spacing between wires ----- 120".

Clearance between conductor and tower 26"

FREQUENCY:

"According to the Standardization Rules of the A.I.E.E. there are two standard frequencies, namely, 60~ and 25~ . In early transmission plants the frequency employed was 60~. All recent transmissions, however, are 25~ , and there

is a strong tendency to lower this frequency to 15 or even 12-1/2 for certain classes of work.

Advantages of 60~ frequency over 25~ frequency:

60~ generators and transformers are smaller and cheaper than those of lower frequency.

Advantages of 25~ frequency over 60~ frequency:

(a) The capacity current, $2\pi f EC$ increases with the frequency. Its effect is to reduce the energy output of the generators and transformers.

(b) The inductive drop, $2\pi f LI$ is less, and consequently the regulation is better than for high frequencies.

(c) The power factor of an induction motor decreases as the frequency is raised.

(d) The lower the frequency, the less difficult becomes the problem of operat-

ing generators and other synchronous apparatus in parallel.

(e) A low frequency is also less liable to set up electrical oscillations as a result of the coincidence of the natural frequency of the line with that of an odd harmonic of the impressed E.M.F." from Sheldon on "A.C. Machines."

From the "Details of Transmission Systems of the World Operating at and Above 70,000 Volts," compiled by Selby Haar, 23 systems operate at 60~, 17 operate at 50~, 6 operate at 25~, 3 operate at 42~, 2 operate at 30~ and 1 at 15~.

The frequency of a transmission line may depend wholly upon the character of the market. If the consumers have machinery demanding electrical energy at a definite frequency there is little choice left to the designing engineer.

The market for electrical energy in this locality of New York state will in all probability demand service at 60~.

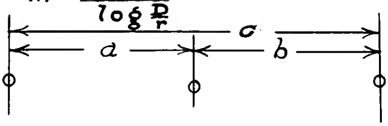
Frequency of transmission ----- 60~.

Line voltage at generating end = 88,000.

Voltage to neutral = $\frac{88,000}{\sqrt{3}}$ = 50,750.

CAPACITY OF ONE LINE TO NEUTRAL:

$C_m = \frac{0.0388}{\log \frac{D}{r}}$ --- per mile in microfarads.



$D = \sqrt[3]{a \times b \times c}$ $\qquad a = 10' \quad b = 10' \quad c = 20'$

$= \sqrt[3]{2000}$

= 12.6' or 151.2".

$r = \frac{.72}{2} = .36''$

$C = \frac{388}{10000} \times \frac{1}{\log \frac{151.2}{.36}} = .01478$ m.f. per mile

INDUCTANCE OF ONE LINE TO NEUTRAL:

Ohms inductive resistance = $\frac{4656}{1,000,000} \times$

$f \times \log\left(2.568 \frac{D}{d}\right)$

$= \frac{4656}{1,000,000} \times 60 \times 2.7324.$

= .765 ohms per mile.

Henrys per mile = $\frac{.765}{2 \times 3.1416 \times 60} = .00203$

DATA ON REGULATION CHART:

Resistance drop at full load =

$$\frac{53 \times 26000 \times 1000}{\sqrt{3} \times 88000} \times .2265 = 2050 \text{ volts.}$$

Inductive drop at full load =

$53 \times 0.765 \times 170.5 = 6{,}930$ volts.

Resistance drop due to charging current:

$$I = 2\pi f C_m l V_n 10^{-6}$$

$$= 2 \times 3.1416 \times 60 \times \frac{1478}{100{,}000} \times 53 \times 50{,}750 \times \frac{1}{1000000}$$

= 15 amperes.

Charging current to be reckoned with =

$\frac{15}{2} = 7.5$ amperes. This correction simply amounts to the assumption that instead of the capacity C, being distributed along the line, a capacity equal to $\frac{C}{2}$ is concentrated at the distant end.

$\therefore$ Resistance drop = $7.5 \times 0.2265 \times 53 =$ 90 volts.

Inductive drop due to charging current =

$7.5 \times 53 \times 0.765 = 304$ volts.

FROM REGULATION CHART:

Terminal voltage at full load = 88,000.

Terminal voltage at no load = 98,400.

Sending voltage at full load = 97,600.

Sending voltage at no load = 97,600.

DISRUPTIVE CRITICAL VOLTAGE:

$$e_o = m_o \delta g_o r \log_\epsilon \frac{s}{r}$$

m_o = 0.85 (for the usual sizes of seven strand cable)

δ = 1

g_o = 21.1 k.v.

r = 0.915 cm. (2.54 x 0.36)

$$e_o = \frac{85}{100} \times 1 \times 21.1 \times \frac{915}{1000} \times \log \frac{\times 120 \times 2.54}{0.915}$$

= 95.4 kilo volts to neutral.

The loss of power due to corona formation is proportional to the frequency (within the usual commercial range), and to the square of the excess of line voltage over critical voltage. Since in this case the disruptive voltage is much in excess of the line voltage

(95,400 - 50,750 = 44,650) the corona loss will be negligible.

INSULATORS FOR SYSTEM:

Apart from the great advantages from the point of view of installation, which are obtained by suspending the conductor from a string of insulators connected in series, this arrangement, as now generally adopted for pressures above 60,000 volts, has the further advantage that the conductor is less liable to be affected by lightning disturbances, since, at every point of support, the wire is hung below the attachment to the supporting structure which, in almost every instance is a well grounded steel structure. Another advantage is the comparative flexibility of the attachment, which very considerably diminishes the possibility of crystallization of the conductor material, such as is liable to occur when the wire is

rigidly attached to the pin type of insulator; this effect being more noticeable with aluminum than with copper.

Generally speaking, the insulators should, when dry, withstand a pressure test of 2-1/2 to 3 times the working pressure to ground, applied for 10 to 15 minutes, and a wet test of not less than 1-1/2 times the working pressure. This would generally be considered too small a margin of safety; but the ratio between test pressure and working pressure will depend upon whether the line voltage is high or low. The altitude of this transmission line averages about 650'. A factor of safety of 2.0 will be used. Insulators are to withstand a voltage of $\frac{88000}{3} \times 2 =$ 101,500 volts or approximately 100,000 volts.

Weight of insulators ------------- 40#

Number of units in series -------- 4

Type ------ Locke Insulator Manufacturing Co. ----- Type used on the Sierra & San Francisco Power Co.

AVERAGE SPAN:

In level country, the economic span for steel tower construction is usually in the neighborhood of 550'. In this case the average span will be 580' except where a deep valley or a high hill necessitates longer or shorter spans.

Height of tower:

$$H = 35 + 0.3\,E_K + 0.6\left(\frac{1}{100}\right)^2$$

$$E = 88000, \quad 1 = 580$$

$$H = 35 + 26.4 + 20.16 = 81.56'$$

The standard flexible and the standard rigid tower will be 75' high.

CALCULATIONS FOR SAG AT DIFFERENT TEMPERATURE SHOWING PULL ON DYNANOMETER:

Maximum loading -- 1/2" coating of ice combined with a wind velocity of 47 miles per hour at a temperature, to = -20° F, n (from curves p. 167 -- Still) = 3.7

$(t_c - t_o)$ (from curves p. 181 -- Still) = 87

$$87 = \frac{T_m}{M \times a} \times \left(1 - \frac{1}{n}\right)$$

$M = 9 \times 10^6$ $\quad a = 1.28 \times 10^{-15}$

$$T_m = 87 \times 9 \times \frac{1000,000 \times 1.28}{0.73 \times 100,000}$$

= 13,750# per square inch.

T_m = maximum loading.

Ultimate strength of wire per square inch =

$$8,070 \times \frac{1}{0.3103} = 25000\#.$$

$$\text{Factor of safety} = \frac{25,000}{13,750} = 1.82.$$

$t_c - t_o = 87^{\circ}$ $\quad k = 0.146$ $\quad t_c = 67.$

$$T_c = \frac{13750}{3.7} = 3,720.$$

$$S_c = \frac{0.146 \times 580 \times 580}{3720} = 13.2'$$

$$C_1 = 8S_c^2 = 8 \times 13.2^2 = 1393.$$

$$C_2 = 3 \times l^2 \times a = \frac{3 \times 580 \times 580 \times 1.28}{100,000}$$

$$= 12.9$$

$$C_3 = \frac{T_c}{Mxa}$$

$$= \frac{3720 \times 10^5}{9 \times 10^6 \times 1.28} = 32.3$$

$$t_c - t = \frac{C_1 - 8\,S^2}{C_2} + C_3 \left(\frac{S_c}{S} - 1 \right)$$

$$67 - t = \frac{1393 - 8S^2}{12.9} + 32.3 \left(\frac{13.2}{12} - 1 \right)$$

When $S = 12$

$$67 - t = \frac{1393 - 1152}{12.9} + 32.3 \left(\frac{13.2}{12} - 1 \right)$$

$t = 45.07^\circ F$

When $S = 8$

$$67 - t = \frac{1393 - 512}{12.9} + 32.3 \left(\frac{13.2}{8} - 1 \right)$$

$t = -22.40^\circ$ F.

When $S = 10$

$$67 - t = \frac{1393 - 800}{12.9} + 32.3 \left(\frac{13.2}{10} - 1 \right)$$

$t = 10.67^\circ$ F.

When $S = 14$

$$67 - t = \frac{1393 - 1568}{12.9} + 32.3 \left(\frac{13.2}{14} - 1 \right)$$

$t = 82.41^\circ$ F.

When $S = 9$

$$67 - t = \frac{1393 - 648}{12.9} \quad 32.3 \left(\frac{13.2}{9} - 1 \right)$$

$t = -5.93^\circ$ F.

When S = 11

$$67 - t = \frac{1393 - 968}{12.9} + 32.3\left(\frac{13.2}{11} - 1\right)$$

$$t = 27.54^{\circ}\ \text{F.}$$

When S = 13

$$67 - t = \frac{1393 - 1352}{12.9} + 32.3\left(\frac{13.2}{13} - 1\right)$$

$$t = 63.19^{\circ}\ \text{F.}$$

TENSION TO BE SHOWN ON DYNAMOMETER:

When

S = 8 ------- T = 1910 pounds.

S = 9 ------- T = 1693 "

S = 10 ------ T = 1525 "

S = 11 ------ T = 1388 "

S = 12 ------ T = 1270 "

S = 13 ------ T = 1174 "

S = 14 ------ T = 1090 "

FLEXIBLE TOWER:

Slope of side member - 1 foot horizontal to 16 feet vertical.

L = length of wire in span.

$$= l + \frac{8s^2}{3l}$$

l = length of span, S = sag of span

$$L = 580 + \frac{8 \times 12^2}{3 \times 12} = 580.6625'$$

Weight per foot of loaded conductor =

$w + 1.254r\ (d + r)$

$= 0.3635 + 1.254 \times .5 \times 1.22 = 1.1295$#/ft.

1 pound per foot will be assumed as the maximum load.

Total vertical load of wires = 6 x 580 x 1 = 3480#.

Weight of ground wire, 3/8" steel cable = 0.345#/ft.

Total weight of ground wire =

0.345 x 580 = 200#.

Wind load on cylindrical surfaces, pounds per square foot = $F = 0.0025 \times V^2$

= 0.0025 x 47 x 47 = 5.525#.

Wind load on ice loaded steel cable =

$$580 \times 5.525 \times \frac{1.362}{13} = 364.\#$$

Wind load per ice loaded aluminum wire

$= 580 \times \frac{1.72}{12} \times 5.525 = 460\#.$

Wind load on flat surfaces, pounds per square foot =

$$F = \frac{36}{10,000} \times V^2 = \frac{36}{10,000} \times 47 \times 47 = 7.95\#$$

Assumed wind load per panel =

$7.95 \times 5 \times \frac{4}{12} = 13.2\#$

(side member assumed 4" x 4" x 1/4")

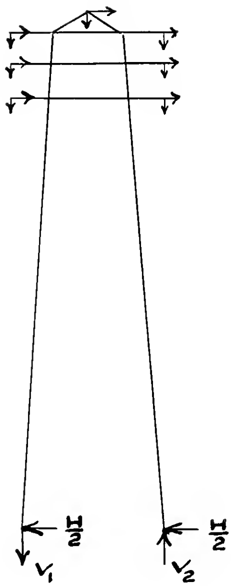
Guard wire is placed 5' above highest cross arm.

Price per pound of finished tower = $ .05

$\frac{H^2}{57}$ = cost of tower. H = height of tower.

Cost of tower $= \frac{75 \times 75}{57} =$ \$98.75

therefore weight of tower $= \frac{98.75}{.05} = 1975\#$ or about 2000#



$H = 364 + 3 \times 460 + 3 \times 473$

$= 3163^{\#}$

$\frac{H}{2} = 1581.5^{\#}.$

$V_2 \times 14 = 2200 \times 7 + 75 \times 364$

$+ 70 \times 933 + 60 \times 933$

$+ 50 \times 933 + 17\frac{1}{2} \times 1740$

$- 3\frac{1}{2} \times 1740.$

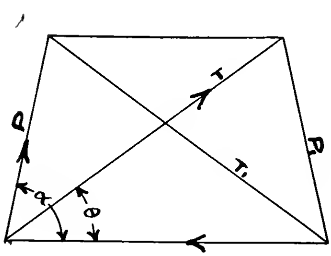
$V_2 = 16,800^{\#}$ compression.

$V_1 \times 14 = 7 \times 2200 - 75 \times$

$364 + 14 \times 1740 - 70 \times 933$

$- 60 \times 933 - 50 \times 933.$

$V_1 = -11,100^{\#}$ tension.



$\theta = 35^{\circ} \quad \alpha = 86^{\circ}\ 45'$

$0 = P \cos\alpha + t \cos\theta - \frac{H}{2}$

$0 = P \sin\alpha + T \sin\theta - V_1$

$P = -12,670^{\#}$ tension

$T = 2740^{\#}$

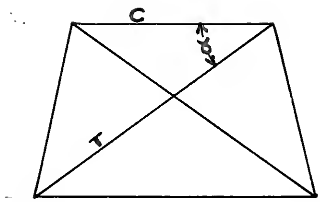
$0 = P_1 \cos\alpha + T_1 \cos\theta - 1581.$

$0 = P_1 \sin\alpha + T_1 \sin\theta - 16800$

$P_1 = 16,300^{\#}$ compression

Not considering T_1,

$P = 16,850^{\#}$ compression



Bottom Panel

$C = \Sigma H$

$C = 364 + 1380 + 1419 = 3163^{\#}$

$T = \Sigma H \sec\alpha$

$= 3163 \times \sec 37\text{-}1/2^{o}$

$= 4000^{\#}$

8" channels - weight $11.25^{\#}$ per foot

strut included.

$\frac{60''}{100} = 0.6$, r of channel = 0.63"

area = 3.35, allowed stress $= 20000 - 70\ \frac{l}{r}$

$= 13000^{\#}$ per square inch.

strength of member $= 13000 \times 3.35 = 43,500^{\#}$

Two angles (⊏⊐) $3\frac{1}{2}'' \times 2\frac{1}{2}'' \times \frac{1}{4}''$, $13.7^{\#}$ per ft.

$\frac{120}{100} = 1.2$, least r of angles = 1.12

actual $\frac{l}{r} = \frac{120}{1.12} = 106$ (Close to 100)

area $= 1.44 \times 2 = 2.88$ square inches

allowed stress $= 20000 - \frac{70 \times 120}{1.12} =$

$12.580^{\#}$ per square inch.

Strength of member = 12,580 x 2.88 =

$36,200^{\#}$

For the side members 2 angles (laced)

$3\frac{1}{2}$" x $2\frac{1}{2}$" x $\frac{1}{4}$" will be used.

Strut. Stress = -3163 length 14'.0"

$\frac{14 \times 12}{120} = 1.4" =$ least r.

Strut will be 2 angles $3\frac{1}{2}$" x $2\frac{1}{2}$" x $\frac{1}{4}$"

(Same as posts)

All lacing will be $1\frac{3}{4}$" x $\frac{1}{4}$" with $\frac{5}{8}$" rivets

Tie rod. Stress = $4000^{\#}$

$\frac{4000}{16000} = \frac{1}{4}$ square inches required.

$\frac{3}{4}$" diameter rod will be used.

Cantilevers.

Bending moment at post = 580 x 8 x 12 =

55,700 inch pounds.

Bending moment at middle (negative) =

580 (10.5 - 4) = 45,250 inch pounds.

Section modulus = $\frac{55700}{16000} = 3.5$

Each angle = 1.75

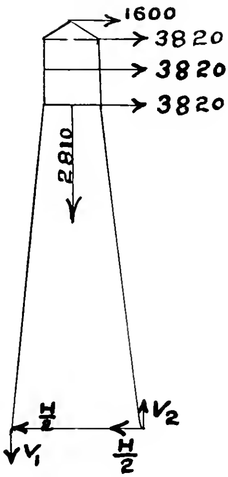
The cantilevers will be 2 angles 5" x 3" x $\frac{5}{16}$"

~~Standard.~~

RIGID TOWER:

Cost of tower $= \frac{75 \times 75}{40} = \$140.50$

Approximate total weight $= \frac{14050}{5} = 2810^{\#}$



Wires are severed on one side of tower close to suspension insulators.

$H = 1600 + 3 \times 3820$

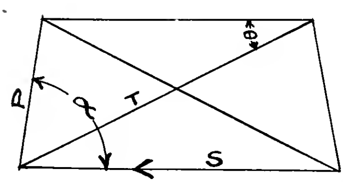
$H = 13060^{\#}$

$\frac{H}{2} = 6530^{\#}$

$24 \times V_1 = 1600 \times 75 + 3820 \times 70 + 3820 \times 60 + 3820 \times 50 - 12 \times 1405$

$V = 33{,}605\#$

$V_2 \times 24 = 1600 \times 75 + 3820 \times 70 + 3820 \times 60 + 3820 \times 50 + 12 \times 2810$



$V_2 = 33{,}595^{\#}$

$\alpha = 81^\circ$

$0 = \Sigma x = 6530 - P \cos 81^\circ + S$

$0 = \Sigma Y = 33595 - P \sin 81^\circ$

$P = 34{,}000\#$ in compression.

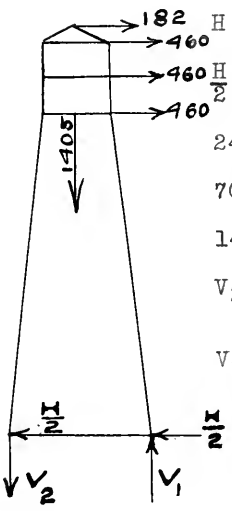
$S = -1210\#$ in tension.

T in tension.

$\Sigma H = T \times \cos 29\frac{1}{2}^{\circ}$

$13,060 = T\times .87$

$T = 15000^{\#}$ (tension)



$H = 1562^{\#}$

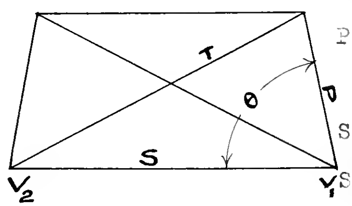
$\frac{H}{2} = 781^{\#}$

$24 \times V_2 = 182 \times 75 + 460 \times 70 + 460 \times 60 + 460 \times 50 - 1405 \times 12.$

$V_2 = 3310^{\#}$

$V_1 \times 24 = 96,450 + 16,850$

$V_1 = 4,720^{\#}$



$781 = P\times \cos \theta + S$

$V_1 = P\times \sin \theta$

$4720 = P\times .9877$

$P = 4,790^{\#}$ compression.

$S = 781 - 750$

$S = 31^{\#}$ compression.

T in tension

$\Sigma H = 1562 = T \times \cos 29\frac{1}{2}^{0}$

$T = 1800^{\#}$

The maximum stresses in any one leg =

$\frac{35400}{2} + \frac{4790}{2} = 17,700 + 2,395$

or approximately $20,000^{\#}$

Design of members of rigid tower.

$T_c = 20,000 - 70 \times \frac{l}{r}$

$= 147''$

$\frac{l}{r} < 100$, $r = 1.47$ r used = 1.54

area of two angles = 6.23×2 =

12.46 square inches allowed stress =

$20,000 - 70 \times \frac{147}{1.54}$

$= 13,300^{\#}$ per square inch.

$13,300 \times 12.46 = 165,600^{\#}$

Since legs will carry more than 8 times the maximum load $\frac{l}{r} < 140$

$147 = r \times 120$, $r = 1.225$

For the legs 2 angles $3\frac{1}{2}'' \times 2\frac{1}{2}'' \times \frac{1}{4}''$ will be used.

Tie Rod,

$0.893 \times 20{,}000 = 17{,}860\#$ per square inch

$1\frac{1}{4}$" diameter rod will be used.

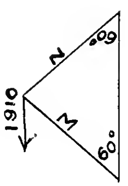
Columns for lateral bracing (S)

length = $12 \times 12 = 144"$

$\frac{144}{120} = 1.2"$ least r

Use same angles as posts, namely, $3\frac{1}{2}" \times 2\frac{1}{2}" \times \frac{1}{4}"$

Cantilevers carrying wires.



$$\frac{1910}{\sin 30^\circ} = M$$

$M = 3820\#$ compression

$N = 3820\#$ tension

Strut = $12" \times 8 = 96"$

$$\frac{l}{r} = 120$$

$96 = r \times 120$

$r = 0.8$

2 angles will be used, $2\frac{1}{2}" \times 2" \times \frac{3}{16}"$

$T_c = 20{,}000 - 70 \times 120$

$= 11{,}600$ pounds per square inch.

$11{,}600 \times 0.81 \times 2 = 18{,}880\#$

Tie rod designed and placed on anchored tower will not give sufficient clearance to line which should be approximately 26" from tower structure. The approximate over-all length of the suspension insulators (4 units) will be $3\frac{1}{2}$'. The arc described by the lowest point of these suspension links will have a minimum clearance of about 22".

Therefore reinforcement of the canti-levers will be accomplished by struts placed as in drawing

Design of strut

$\frac{l}{r} = 140$, $l = 96"$

$r = \frac{96}{140} = 0.686$

1 angle $2\frac{1}{2}" \times 2" \times \frac{3}{16}"$ will be used

$r = 0.79$

$580 = P \times \sin 28^{\circ}$

$P = 1240^{\#}$

area of angle = 0.81 sq. inches.

safe stress $= 20,000 - 70 \times \frac{96}{.79} - 11,500^{\#}$ per sq. inch.

$0.81 \times 11,500 = 9,310^{\#}$

Member is therefore safe.